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# DEPARTMENT OF DEFENCE

## DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

## MATERIALS RESEARCH LABORATORIES

MELBOURNE, VICTORIA

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**REPORT**

**MRL-R-830**

METAL JET INITIATION OF BARE AND COVERED EXPLOSIVES; SUMMARY OF THE MECHANISM, EMPIRICAL MODEL AND SOME APPLICATIONS

M.C. Chick and D.J. Hatt



Approved for Public Release





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The paper summarises an investigation aimed at determining the mechanisms and factors that control the sensitivity of bare and covered explosives to attack from shaped charge jets. The mechanism of the initiation process has been studied using multiple flash X-radiography. A test is described that assesses the sensitivity of explosives to a jet in terms of the thickness of a steel barrier that will allow detonation in 50% of the firings.

The general mechanism proposed is illustrated by systems that produce strong initiating shocks, weak initiating shocks and failure shocks in Composition B.

An empirical model is described which calculates the pressure of jet impact, and follows the shock produced through the steel covering and into the explosive. Calculated shock pressures and corresponding velocities in Composition B are in good agreement with those determined experimentally. The shock pressure profile through the steel barrier in the empirical model is used to convert the measured critical barrier thicknesses to the critical initiating shock pressures for four explosives, (creamed TNT, Composition B, pressed TNT, pressed Tetryl). These calculated critical pressures are compared to the critical pressures obtained from the NOL Large Scale Gap Test. The agreement is excellent.

Some possible applications of the action of the jet and desensitisation of explosives by preshocking to Explosive Ordnance Disposal and warhead design are briefly discussed.



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Continued on next page

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CONTENTS

# METAL JET INITIATION OF BARE AND COVERED EXPLOSIVES; SUMMARY OF THE MECHANISM, EMPIRICAL MODEL AND SOME APPLICATIONS

## 1. INTRODUCTION

There is considerable worldwide awareness of the vulnerability of explosive filled munitions to, and the potential catastrophic effects from, untimely detonation by both enemy weapons during wartime and accidents or saboteurs in peacetime. One concern is that the explosive fillings in bombs and missiles on aircraft, missiles and stores on the decks of ships, and shells inside fighting vehicles are susceptible to attack from shaped charge jets and certain types of projectiles. The situation might be able to be partly rectified if there was a better understanding of the processes involved when a jet or projectile interacts with a munition case and explosive filling. Such information might permit improved hardening of friendly weapons against enemy attack as well as assist in controlled explosive ordnance disposal.

This report summarises an investigation aimed at determining the mechanisms and factors that control the sensitivity of bare and cased explosives to attack from shaped charge jets. The mechanism of the initiation process has been studied using Composition B. The sensitivity of other explosives to shaped charge jets has also been assessed.

## 2. EXPERIMENTAL

### *2.1 Method of Investigating the Mechanism of Jet Initiation*

A schematic diagram of the experimental arrangement is shown in Fig. 1 and has been previously reported [1,2]. The flash X-ray equipment has been described previously [3,4]. Flash X-ray synchronization was achieved by means of an electric sensor placed between the steel barrier and the receptor charge. Jet penetration of the sensor triggered the two 300-kV flash X-ray units. Two orthogonal radiographs were taken at different times for each firing; delayed timing for the X-ray flashes was based on the calculated

position of the jet, shock, or phenomenon under study and was obtained by means of a digital delay pulse generator. Several firings were conducted for each steel barrier thickness studied. The known dimensions of the explosive and steel components were used to obtain scaled distance measurements from the radiographs.

The metal jet was generated from a conventional 38 mm diameter shaped charge with a copper liner of 42° apex angle filled with Composition B[5]. It will penetrate about 177 mm of mild steel. The shaped charge was fired from a standoff of 76 mm (2 charge diameters) through a predetermined thickness of mild steel which was in intimate contact with a 38 mm diameter cylinder of the receptor explosive. Detonation of the receptor charge was detected by a sharp dent in the steel witness block.

The composition B used for the shaped charges and receptor charges was a RDX/TNT/WAX (45/55/1) mixture of density 1.65 $g/cm^3$ with 5.0% voidage. The quality of both charges was checked by radiography. Generally, the receptor charge length was 102 mm but some other lengths were used when studying effects closer to and further from the explosive/barrier interface.

The thickness of the barrier was varied in order to alter the characteristics of the jet and precursor shock entering the explosive. This was based on the assumption that as the barrier thickness is increased, the jet penetration velocity decreases and a weaker precursor shock is produced.

In some experiments a 15 mm wide air gap was introduced between the steel barrier and Composition B in order to remove the precursor shock. For these rounds the flash X-ray trigger was maintained in contact with the underside of the steel barrier. The penetration velocity of the jet through the steel was measured and substituted into the classical shaped charge theory equation [6] to give the emerging jet velocity in air. By assuming that this velocity was constant the time for the jet to traverse the air gap was estimated.

### *2.2 Assessment of the Sensitivity of Explosives to Shaped Charge Jets*

The experimental test arrangement is similar to that shown in Fig. 1 but the flash X-ray system was not used. The test operated on similar principles to the gap test [7,8]. A standard shaped charge is fired from the fixed standoff distance through a variable steel barrier into a 38 mm diameter cylinder of the explosive under test. For each explosive, 20 charges were fired using the Bruceton staircase procedure to determine the critical steel barrier thickness required to produce detonations in 50% of the firings.

The explosives tested were creamed TNT, pressed TNT and pressed Tetryl. Table 1 gives the test results together with the explosive charge lengths, densities and shock sensitivities measured on the MRL small scale gap test. The Composition B critical barrier thickness value given in Table 1 was determined as part of the experiments described in section 2.1 above.

# 3. RESULTS AND DISCUSSION

## *3.1 Summary of the General Mechanism of Initiation*

The authors have recently reported [1,2] aspects of the initiation of steel-covered Composition B which are summarised below.

When the high speed metal jet impacts the steel surface a shock is produced (termed the precursor shock) which races ahead of the jet, enters the Composition B and either runs to detonation or fails, depending on the shock strength. The jet continues to penetrate the steel barrier and enters the explosive behind the shock; for the systems under study this lag can be between 1 and 3 μs and 5 and 11 mm depending on the steel barrier thickness. Close to the onset of detonation a retonation is observed moving back through the previously shocked explosive which is expanding radially.

The jet does not directly produce detonation even though it produces a large shock pressure on impact with the Composition B at the steel/Composition B interface. This pressure is estimated to be up to $7\frac{1}{2}$ times greater than the precursor shock pressure. The run and time to detonation increase with increasing barrier thickness and decrease with increasing precursor shock pressure set up in the explosive. For the critical barrier thickness, the run distance and time to detonation for Composition B are about 50 mm and 15 μs respectively. The critical shock pressure to produce detonation is about 2.6 GPa.

Removal of the precursor shock (by the introduction of an air gap between the Composition B and steel barrier) considerably increased the sensitivity of the Composition B to jet impact alone and dramatically decreased the run and time to detonation; the critical barrier thickness increased from about 60 mm to between 89 and 102 mm. It is clear therefore that the precursor shock desensitises the explosive and stops the jet from directly initiating detonation.

Desensitisation of explosives by preshocking has been observed by others [9,10,11] and may be explained as follows. The first shock causes collapse of voids, etc. and the creation of hot spots with chemical reaction. Some of the energy is released quickly enough to feed the passing shock front. The remaining energy is slowly dissipated to the surroundings. However, the region remains compressed and the voids remain collapsed. The explosive is left in a more homogeneous state and will be less sensitive to a closely following shock(s). The compressed state will last until released by a rarefaction wave. The explosive will then be subjected to tension, will craze and disintegrate and once again will become sensitive to shock. Indeed the crazed explosive can be expected to contain greater voidage and surface area than the original explosive and hence be more sensitive to shock.

When applied to the current study, the mechanism suggests that the high pressure shock from the jet impact on the explosive at the steel/explosive interface follows the precursor shock within the zone under compression while the retonation moves through the explosive which is breaking up under tension.

The mechanism can be used to postulate an explanation for the failure to observe retonations in some experiments. In the study reported herein non ideal shocks are produced. Therefore, when the abrupt transition to detonation occurs at the shock front the disturbance is able to communicate around or through the thin and curved compressed, desensitised zone behind the shock front to reach the explosive sensitised by the rarefraction. A retonation then breaks out. However, in the ideal shocks reported by Campbell et al [9], the abrupt onset of detonation produces a disturbance that is unable to effectively span the compressed, desensitised zone which is thick and planar. This indicates that the important factor for the production of a retonation in the build-up process is the thickness of the shock.

### *3.2 Observed Characteristics of Jet Initiation of Composition B*

Various characteristics of shaped charge jet initiation and penetration of Composition B are shown in the flash radiographs of Figs 2a to h.

Figs 2a and b show flash X-radiographs of the effect of the jet penetrating a 12.5 mm thick barrier. A strong precursor shock is produced with detonation having occurred close to the barrier/Composition B interface. The jet continues to penetrate the detonation products and various shock reflections can be observed. Fig. 2b also shows that the front portion of the jet is unstable and is in the process of being blown apart.

Jet initiation of Composition B covered by a 51 mm thick steel barrier produced a weak precursor shock that required a long run and time to achieve detonation. Figs 2c and e show examples of flash X-radiography of Composition B with a shock ahead of the jet, the shock to detonation transition and the detonation and retonation combination well established.

Figs 2f and g show flash X-radiographs of a jet failing to initiate Composition B through a 63.5 mm thick barrier. The shock was always observed ahead of the jet but both velocities decreased with distance. In Fig. 2f the expansion of the Composition B can be observed after 25 μs of jet entry. Fig. 2g taken after 140 μs of jet entry shows the expansion of Composition B as a cloud with no bulk reaction detectable. Powdered explosive (shown by analysis to be Composition B) was recovered from the walls of the firing cell. These experiments clearly demonstrate that, contrary to popular belief, a shaped charge jet can pass through an explosive without producing detonation.

The effect of removing the precursor shock by the introduction of an air gap between the steel barrier and Composition B is shown in Fig. 2h for an

89 mm barrier. Detonation is well advanced after 4.3 μs of jet entry with the onset of detonation estimated to have occurred before 2 μs and 11 mm - without an air gap the explosive would have failed to detonate. The effect of the removal of the precursor shock was further demonstrated by the introduction of an air gap about half way along the 40 mm run to detonation distance fc·· the 51 mm barrier system, thereby allowing jet impact on bare Composition B that had not been preshocked. Flash X-radiography showed that the first 20 mm of Composition B in contact with the steel barrier did not detonate but that prompt detonation occurred close to the bare surface of the Composition B on the far side of the air gap.

The measurements from the flash X-radiographs have been used to construct space/time plots for various barrier thicknesses and steel barrier/air gap combinations. Examples are shown in Figs 3a to c.

The strong precursor shock case from a 12.5 mm thick steel barrier is shown in Fig. 3a. Note that detonation has occurred prior to jet entry into the explosive and close to the interface. Fig. 3b shows initiation through a 51 mm thick steel barrier. The weak precursor shock ran 40 mm for 11 μs before the abrupt transition into detonation. The shock is always ahead of the jet and the preshocked zone would at least cover the distance between the two lines. The measured detonation velocity of 7.77 mm/μs is very close to the BKW Code value of 7.762 mm/μs calculated using experimental parameters [12]. Because of the good agreement the latter value was used to construct the velocity of detonation line for the other space/time plots.

Fig. 3c shows a shock that failed to initiate Composition B and was always ahead of the jet.

Table 2 lists the measured jet and shock velocities in Composition B determined using the best fit equations to the data for various thicknesses of steel barriers. Also listed are the run distances and times to detonation. Generally, the jet and shock velocities decrease with increasing barrier thickness. The reason for the low jet velocity for the 19 mm barrier is not understood. Both the run distance and time to detonation increase with increasing barrier thickness and decreasing precursor shock pressure.

The pressure of the shock wave is an important property when considering the shock initiation of explosives. Shock velocity, Us, can be related to shock pressure, P, by the hydrodynamic relationship [13],

$$P = U_s U_p \rho \qquad (1)$$

where $\rho$ = initial density, and

$U_p$ = particle velocity behind the shock.

Since for Composition B, ρ and 's have been measured and the relationship between Up and Us is known [14], the shock pressure can be determined. These values are given in Table 3 as the experimentally determined shock pressures.

The results show that as the shock pressure was decreased the run and time to detonation increased. The values are in good agreement to those from a recent study of the shock initiation characteristics of Composition B assessed on the NOL Large Scale Gap Test by Mader et. al. [15]. These observations are consistent with a shock initiation mechanism which is further supported by the similar trend in the results from both the Gap Test and Shaped Charge Jet Sensitivity Test for the explosives tested in Table 1.

### *3.3 An Empirical Model for the Jet/Precursor Shock Initiation of Covered Explosives*

The general mechanism proposed for the jet initiation of covered explosives has been used to calculate the pressure of the precursor shock from jet impact and follow the shock through the steel cover into the explosive. A detailed description of the empirical model is described elsewhere [16].

The jet is considered as a small diameter projectile of copper impacting the steel surface at right angles. The shock pressure created by the impact is determined from equation (1), where ρ = initial density of copper, Up = $\frac{1}{2}$ jet velocity and the relationship between Up and Us is known [17].

The shock pressures across the copper/steel and steel/Composition B interfaces are determined from the established pressure (P) vs particle velocity (Up) curves (Hugoniots) for the materials [14,17]. The variation of the shock pressure through steel is obtained using the geometrical relationship [18],

$$P_{S'} = P_{S^o}\left[\frac{1}{1+\sqrt{2}\left(\frac{x}{d}\right)}\right] \qquad (2)$$

where:

$P_{S'}$ = shock pressure in steel at the exit surface of the steel barrier,

$P_{S^o}$ = shock pressure in steel at the entry surface of the steel barrier,

d = jet tip diameter, and

x = steel barrier thickness.

Having calculated the shock pressure in Composition B the corresponding shock velocity can also be determined using equation (1).

The shock pressures and corresponding velocities in Composition B calculated using the empirical model are compared to the experimentally determined values in Table 3 for several barrier thicknesses. There is good agreement for both shock pressures and velocities. There is also the indication that the experimental values estimated from the few firings for the 57 mm thick barrier are low.

The shock pressure profile through the steel barrier in the empirical model was used to convert the critical barrier thickness to the critical shock pressure to initiate Composition B. Similar calculations have been performed for the other explosives listed in Table 1 using the determined critical barrier thicknesses and the appropriate shock Hugoniots reported by Boyle et. al. [14].

The calculated critical initiating shock pressures for cast TNT, Composition B, pressed TNT and Tetryl are given in Table 4 and compared with the critical shock pressures determined on the NOL Large Scale Gap Test [8]. Although there are variations in densities of the corresponding explosives, and other charge characterisations such as particle size are not known, the agreement is excellent. The geometries of the receptors and some of the other components for the two tests were similar but the initiating devices were entirely different - a metal jet compared to a detonating donor. Therefore, the excellent agreement in the two sets of results suggests that the net effect of the initiating stimulii on the receptor charges for the two tests were similar.

The success of the empirical model as shown by the data in Tables 3 and 4 suggests there may be some benefit in using the model to predict the effect of shaped charge jets on covered explosives. Thus if the critical initiating pressure for an explosive is known (from Large Scale Gap Test or the Shaped Charge Jet Sensitivity Test) then the minimum thickness of steel required to stop the detonation (or the converse) of the explosive filling can be estimated for shaped charge jets of various diameters, velocities and materials [16]. For example Fig. 4 shows the predictions from the empirical model for the effect of various diameter copper jets on steel covered Composition B. Further experiments are planned to test these predictions.

*3.4 Possible Applications of the Study Results*

The current status of the study allows some speculation of the application of the results.

The mechanism of the initiation of covered explosives suggests that the vulnerability of munition fillings to shaped charge jets can be reduced by avoiding air gaps adjacent to the explosive which would remove the desensitising effect of the precursor shock. Hence the work has demonstrated the need to ensure that the explosive filling is in contact with the casing after production and during the munition's life in storage and transport. Furthermore it may be possible to determine the thickness of protective material that would be required to be placed around the munition or warhead

(vehicle wall, compartment wall, munition storage bin, guidance equipment, munition casing, etc.) in order that the jet/shock combination could not detonate the explosive. There ma/ well be some disruption but the catastrophic effect of a detonation would be avoided. Clearly it would also be of benefit to reduce the shock sensitivity of the explosive.

The dramatic sensitising effect of the air gap by removing the desensitising percursor shock also suggests applications in the field of Explosive Ordnance Disposal. Thus when shaped charge jets are used for this purpose the jet should be aimed away from any position in the munition where there is an air gap in contact with the explosive or where there is a more sensitive booster pellet. Again the study suggests that if the characteristics of the EOD shaped charge jet device are known then it may be possible to determine the minimum amount of material to be added to the outside of the casing to stop the jet from detonating the filling. This could assist in producing either a detonation or failure as required.

The desensitisation of explosives by preshocking in engineering and munition systems has general applications. For example the malfunction of an explosive train system under examination at MRL is currently considered to result from a shock travelling down the wall of a steel case ahead of the detonation, preshocking the explosive filling and extinguishing reaction [19]. This is a reasonable postulation in view of the findings reported herein and the preshocking experiments reported by Mader [10] where detonating TATB was extinguished by a shock generated from flying plate impact on the side of the charge.

The observations and proposed mechanism indicate that the jet tip continually penetrated the target explosive within the compresed zone behind the precursor shock front. Thus the classical hydrodynamic theory of jet penetration may require modification to take account of the increased density of the target explosive due to shock loading. A preliminary estimate of the magnitude of the effect has been undertaken and reported [1] for the jet penetration of Composition B and steel targets. Factors such as target hardness and strength were ignored. The study showed that although the precursor shock substantially increased the density of low density materials such as explosives (for the example considered about 15%), the effect on the jet penetration characteristics was small. Further the effect would appear to be negligible on both the density and jet penetration characteristics of high density, targets such as steel. However, the full implications of a jet penetrating within the compressed zone of shocked target materials requires further analysis.

## 4. ACKNOWLEDGEMENTS

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## TABLE 1

## CHARACTERISTICS AND RESULTS OF EXPLOSIVES ASSESSED FOR SENSITIVITY TO SHOCK AND A SHAPED CHARGE JET

| EXPLOSIVE | DENSITY | | | SHOCK SENSITIVITY, GAP TEST VALUE | SHAPED CHARGE JET SENSITIVITY | |
|---|---|---|---|---|---|---|
| | TMD $g/cm^3$ | ACTUAL $g/cm^3$ | VOIDS % | ins x $10^{-3}$ | CRITICAL BARRIER THICKNESS mm | CHARGE LENGTH mm |
| CREAMED TNT | 1.654 | 1.57 | 5.08 | > 0 | 24 | 102 |
| COMP B | 1.738 | 1.65 | 5.04 | 15.6, 15.1 | ≃ 60 | 102 |
| PRESSED TNT | 1.654 | 1.52 | 8.10 | 48 | 104 | 51 |
| PRESSED TETRYL | 1.73 | 1.48 | 14.45 | 111.6 | 136 | 51 |

## TABLE 2

## SUMMARY OF DATA FOR JET INITIATION OF COMPOSITION B THROUGH STEEL BARRIERS

| BARRIER THICKNESS mm | INITIAL JET VELOCITY IN COMP. B OR PRODUCTS mm/μs | SHOCK VELOCITY IN COMP. B mm/μs | RUN DISTANCE TO DETONATION mm | TIME TO DETONATION μs |
|---|---|---|---|---|
| 12.5 | 5.6 ± 0.2 | | | |
| 12.5 with air gap | 5.6 ± 0.5 | | | |
| 19 | 3.96 ± 0.2 | | ≃ 16 | ≃ 4.8 |
| 25 | 5.1 ± 0.2 | 4.4 ± 0.5 | 21.7 ± 0.1 | 4.9 |
| 51 | 4.25 ± 0.07 | 3.7 ± 0.3 | 40.3 ± 3.5 | 11.0 |
| 57 | 3.10 ± 0.02 | ≃ 3.4 | ≃ 50 | ≃ 15 |
| 63.5 | 3.6 ± 0.03 | 3.7 ± 0.07 | FAILED | FAILED |

## TABLE 3

## COMPARISON OF CALCULATED AND EXPERIMENTALLY DETERMINED PRECURSOR SHOCK CHARACTERISTICS IN COMPOSITION B

| BARRIER THICKNESS | SHOCK VELOCITY | | INITIAL SHOCK PRESSURE | |
|---|---|---|---|---|
| | EXPERIMENTAL | CALCULATED | EXPERIMENTAL | CALCULATED |
| mm | mm/µs | mm/µs | GPa | GPa |
| 12.5 | | 5.16 | | 11.8 |
| 19 | | 4.60 | | 8.0 |
| 25 | 4.4 | 4.36 | 6.9 | 6.2 |
| 51 | 3.7 | 3.71 | 2.7 | 3.0 |
| 57 | ≃ 3.4 | 3.65 | ≃ 1.6 | 2.7 |
| 63.5 | 3.7 | 3.60 | 2.8 | 2.5 |

## TABLE 4

## COMPARISON OF CRITICAL SHOCK PRESSURES FOR THE MRL JET TEST AND NOL LARGE SCALE GAP TEST INITIATION FOR SEVERAL EXPLOSIVES

| EXPLOSIVE | MRL SHAPED CHARGE JET SENSITIVITY TEST | | NOL GAP TEST |
|---|---|---|---|
| | CRITICAL BARRIER THICKNESS<br>mm | PRECURSOR SHOCK PRESSURE IN EXPLOSIVE<br>GPa | CRITICAL SHOCK INITIATION PRESSURE IN EXPLOSIVE<br>GPa |
| CREAMED TNT ($\rho$ = 1.57 g/cm$^3$) | 24 | 6.0 | 5.27 ($\rho$ = 1.60 g/cm$^3$) |
| COMP. B ($\rho$ = 1.65 g/cm$^3$) | ≃ 60 | 2.6 | 2.48 ($\rho$ = 1.70 g/cm$^3$) |
| PRESSED TNT ($\rho$ = 1.52 g/cm$^3$) | 104 | 1.4 | 2.0 ($\rho$ = 1.49 g/cm$^3$) |
| PRESSED TETRYL ($\rho$ = 1.48 g/cm$^3$) | 136 | 0.7 | 0.85 ($\rho$ = 1.49 g/cm$^3$) |

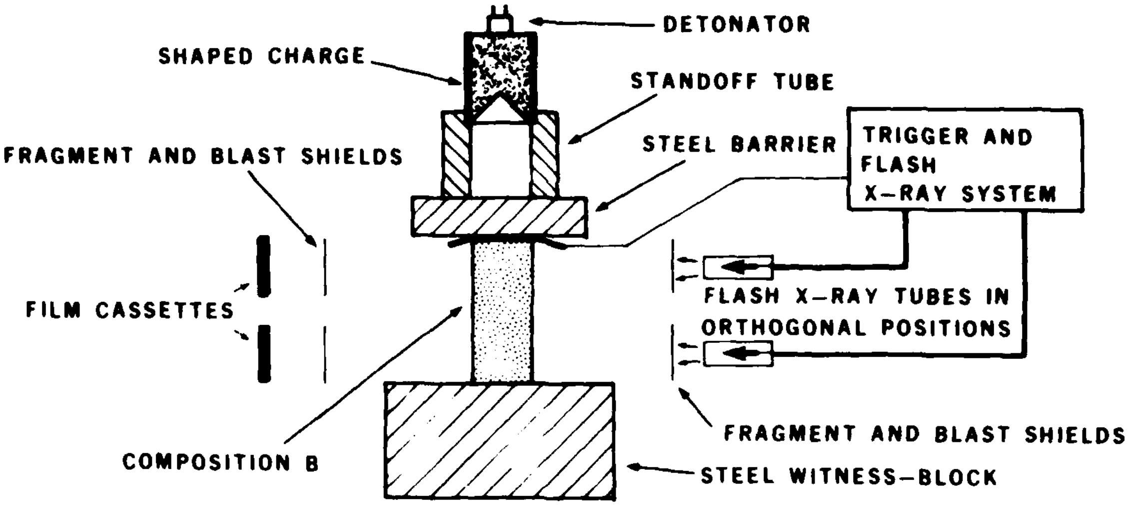


FIG. 1 - Experimental arrangement for the flash X-ray study of the initiation of Composition B by a metal jet.

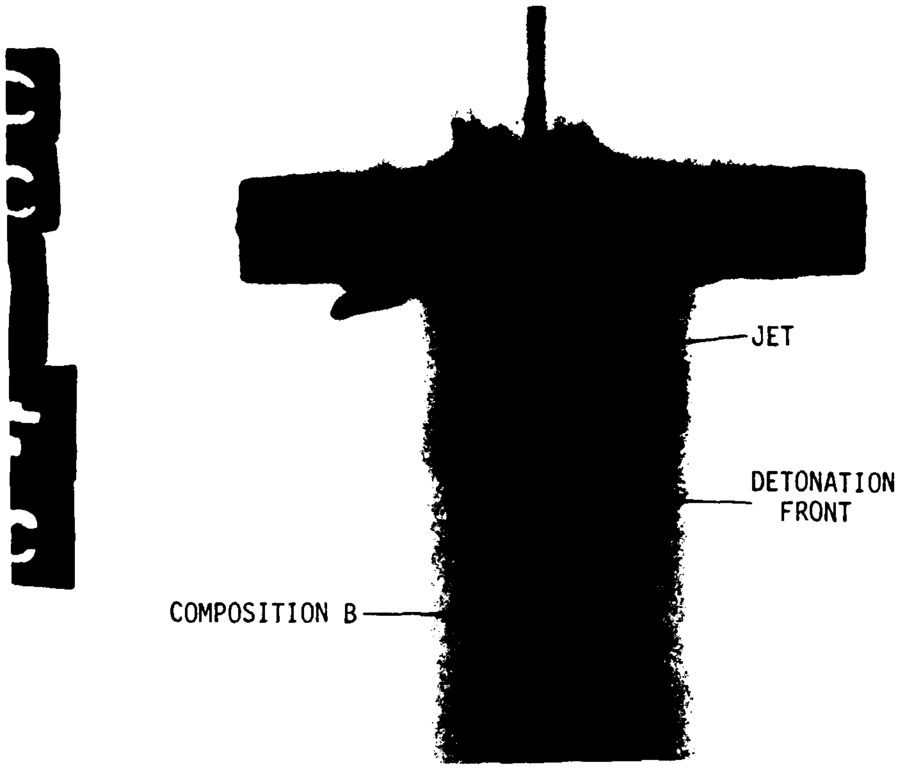


FIG. 2(a) - Flash radiograph after 2.1 μs showing detonation for 12.5 mm barrier.

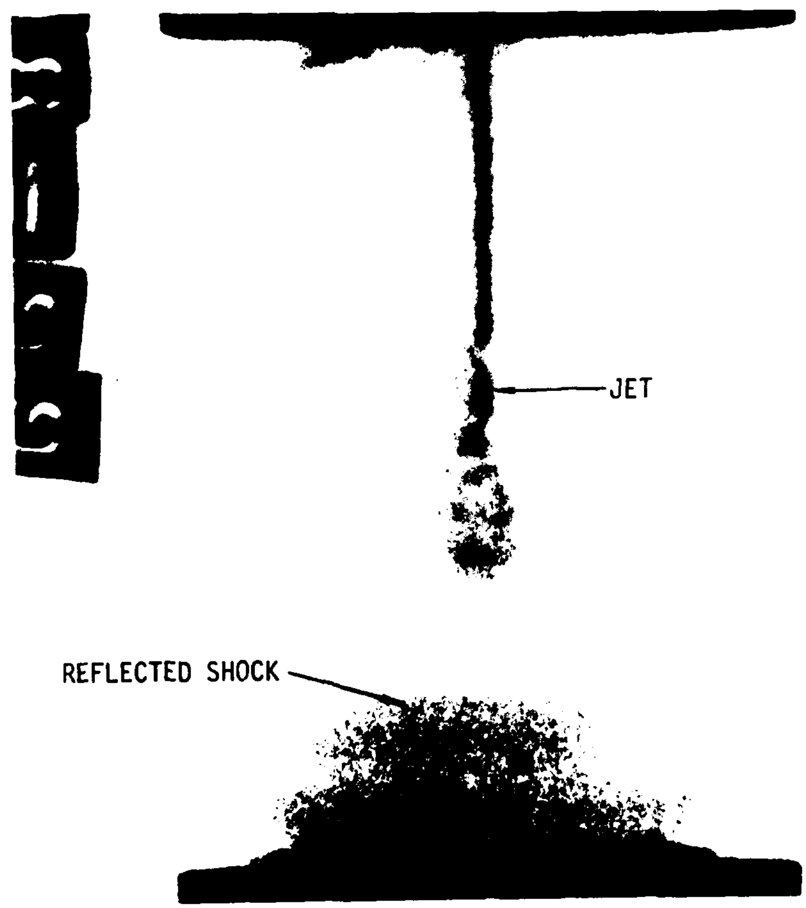


FIG. 2(b) - Flash radiograph after 18.7 μs showing jet and detonated explosive for 12.5 mm barrier.

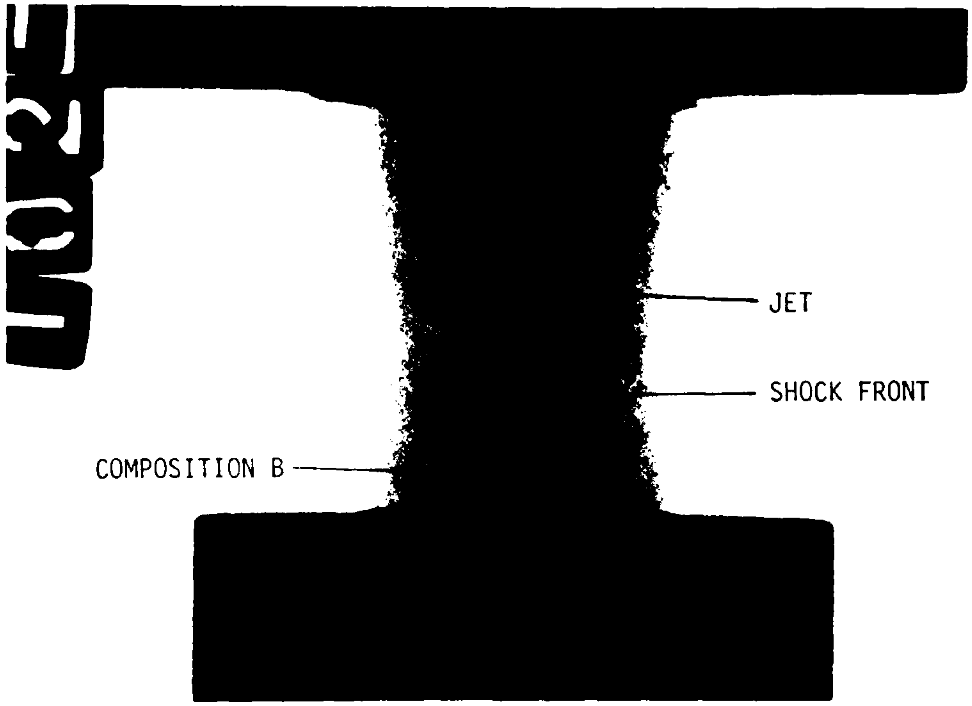


FIG. 2(c) - Flash radiograph after 9.0 µs showing shock ahead of jet for 51 mm barrier.

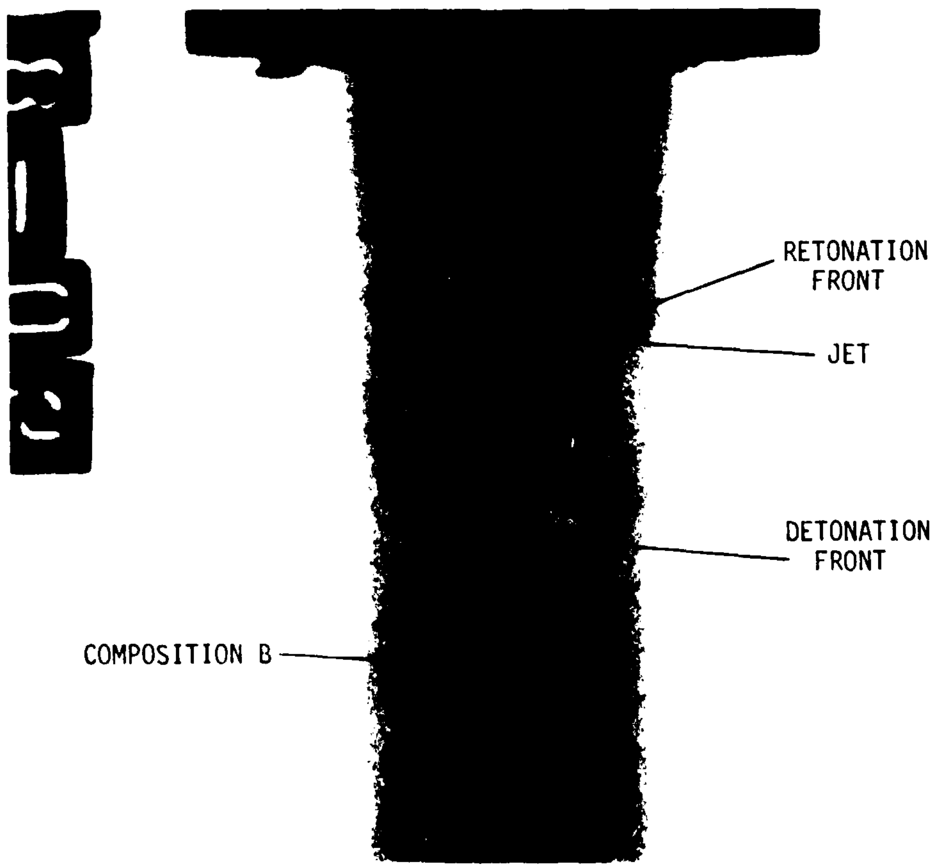


FIG. 2(d) - Flash radiograph after 11.9 µs showing shock/detonation transition for 51 mm barrier.

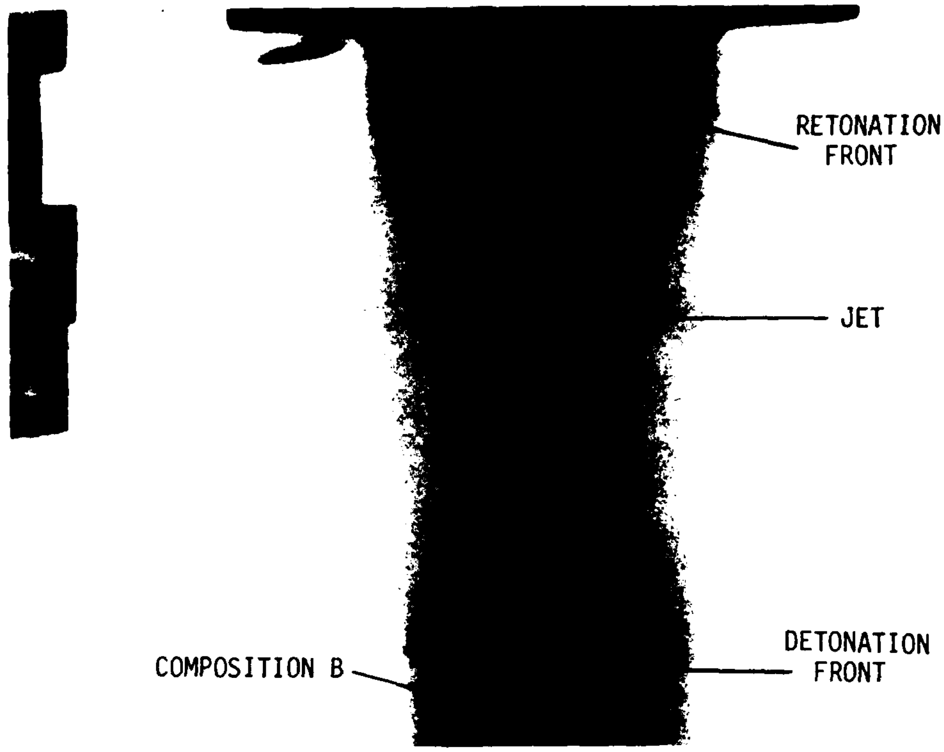


FIG. 2(e) - Flash radiograph after 14.4 μs showing detonation and retonation for 51 mm barrier.

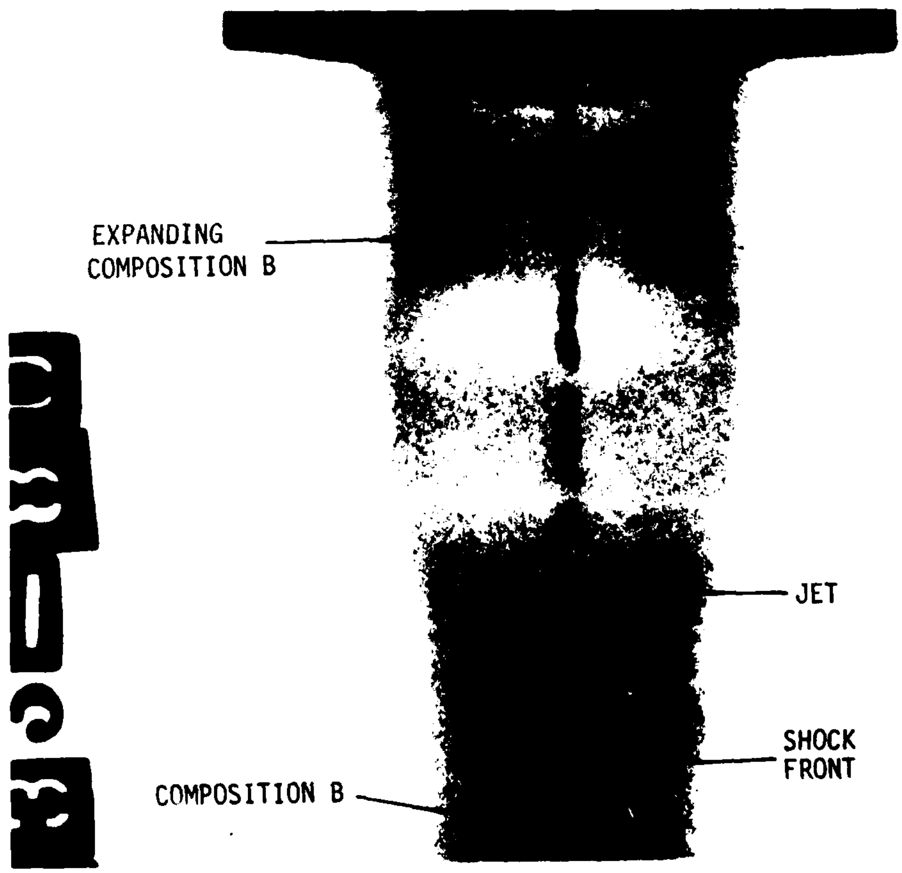


FIG. 2(f) - Flash radiograph of failure for 63.5 mm barrier showing shock and jet after 25.0 μs.

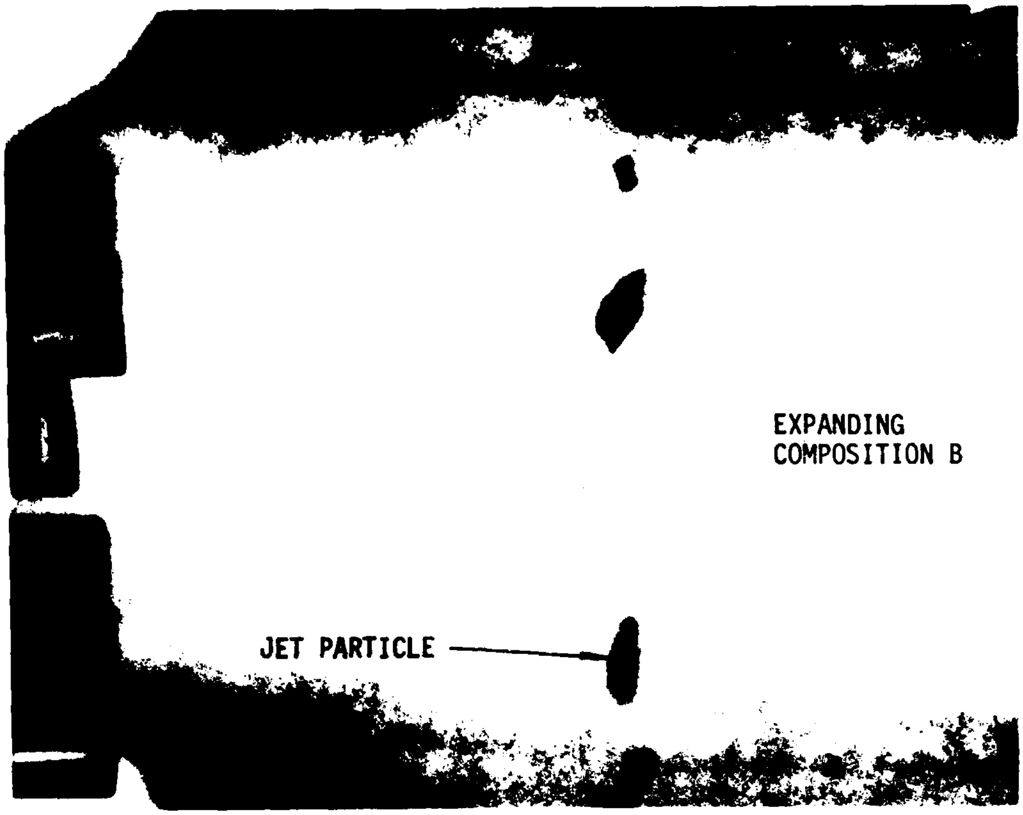


FIG. 2(g) - Flash radiograph after 140 μs showing expanding, failed Composition B for 63.5 mm barrier.

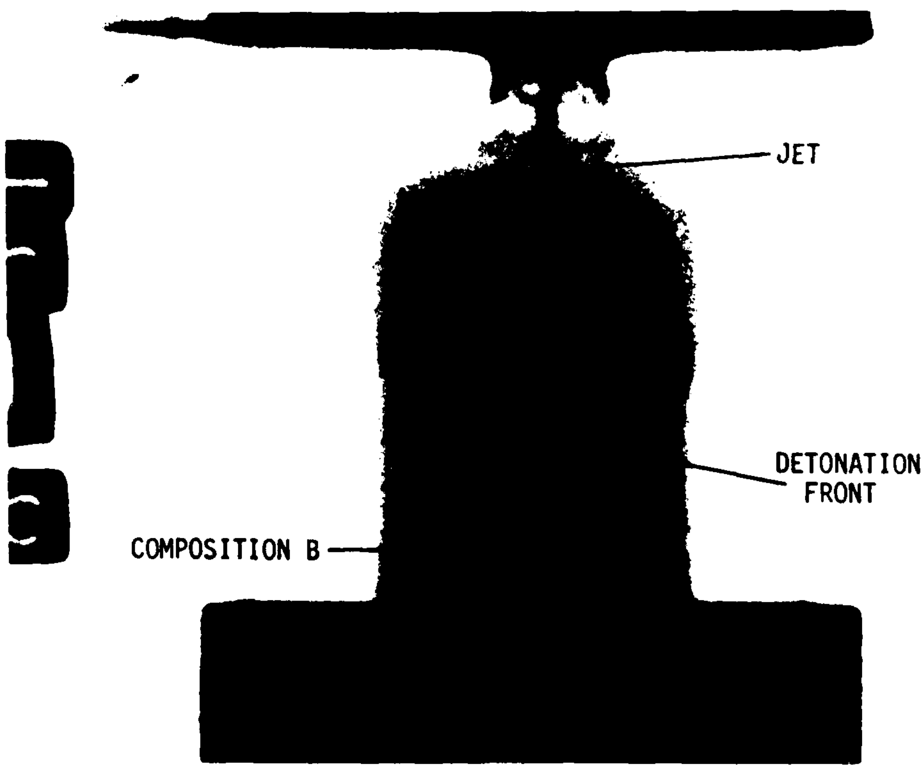


FIG. 2(h) - Flash radiograph after 4.3 μs showing detonation for the air gap/89 mm barrier system.

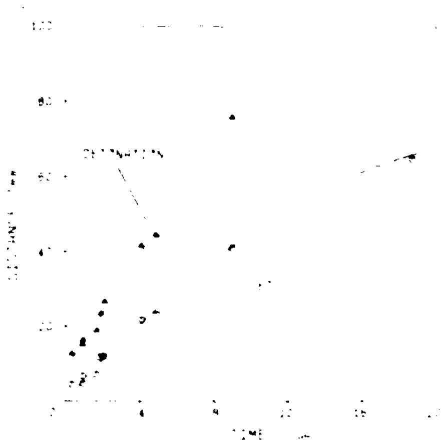

FIG. 3(a) - Space/time plot for 12.5 mm barrier.

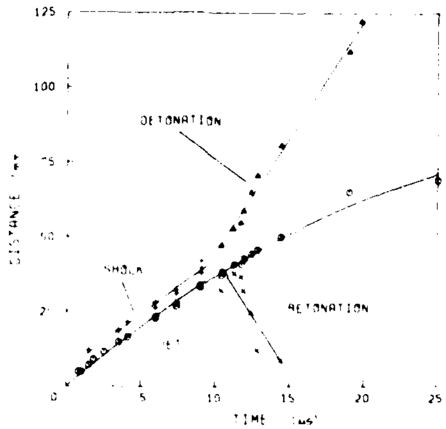


FIG. 3(b) - Space/time plot for 51 mm barrier.

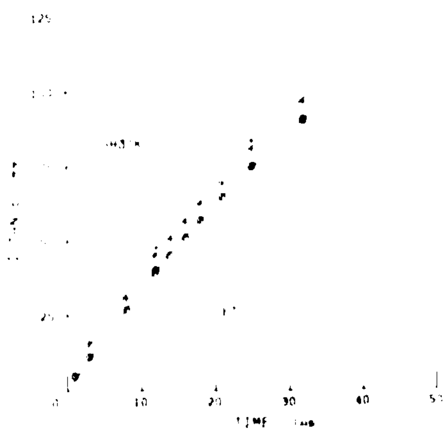


FIG. 3(c) - Space time plot for 63.5 mm barrier.

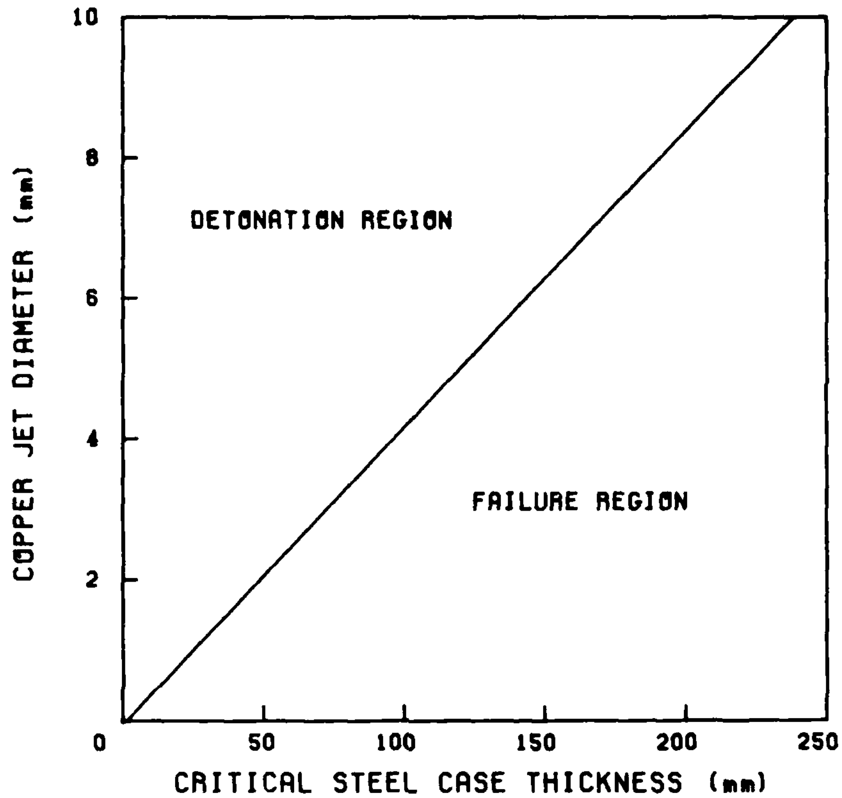


FIG. 4 - Empirical model estimates of the critical case thickness for various diameter jets to initiate Composition B.

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